Non - Metallic Materials
Prof. Subhasish Basu Majumder
Department of Materials Science Centre
Indian Institute of Technology, Kharagpur

Module - 05
Electrical, magnetic and thermal properties of non - metallic materials
Lecture - 24
Ferroelectric behavior of non - metallic materials and ferroelectric thin film for non - volatile memory applications

Welcome to my course Non – Metallic Materials. And we are in module number 5, Electrical, magnetic and thermal properties of non–metallic materials. And this is lecture number 24, Ferroelectric behavior of non–metallic materials and ferroelectric thin film for non–volatile memory applications.

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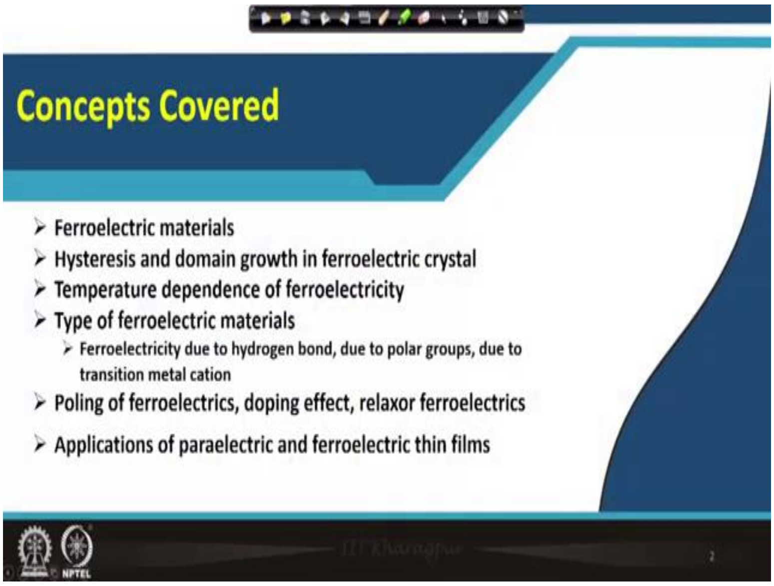

Concepts Covered

- Ferroelectric materials
- Hysteresis and domain growth in ferroelectric crystal
- Temperature dependence of ferroelectricity
- Type of ferroelectric materials
  - Ferroelectricity due to hydrogen bond, due to polar groups, due to transition metal cation
- Poling of ferroelectrics, doping effect, relaxor ferroelectrics
- Applications of paraelectric and ferroelectric thin films

Last lecture we talked about the linear dielectric material. When you are applying an electric field the material gets polarized; as soon as the field is there, the polarization is there. Once the field is 0, then polarization also turns to be 0. Now, this particular material which we are calling ferroelectric material, they are basically non-linear dielectric.

So, their relationship between polarization and electric field is non-linear in nature. So, we will be talking about this material. Then we will talk about the hysteresis loop characteristics, which is the fingerprint of ferroelectric material and its interrelation with domain growth. Then we will talk about the temperature dependence of this ferroelectric nature. We will introduce various types of ferroelectric materials.

And then we will introduce the concept of DC poling of this material and the doping effect to change their properties, and a special type of material which is not ferroelectric, but very similar to this, this is relaxer material is having extraordinary high dielectric permittivity. And certain applications of ferroelectric material both in their paraelectric as well as ferroelectric phase will be described.

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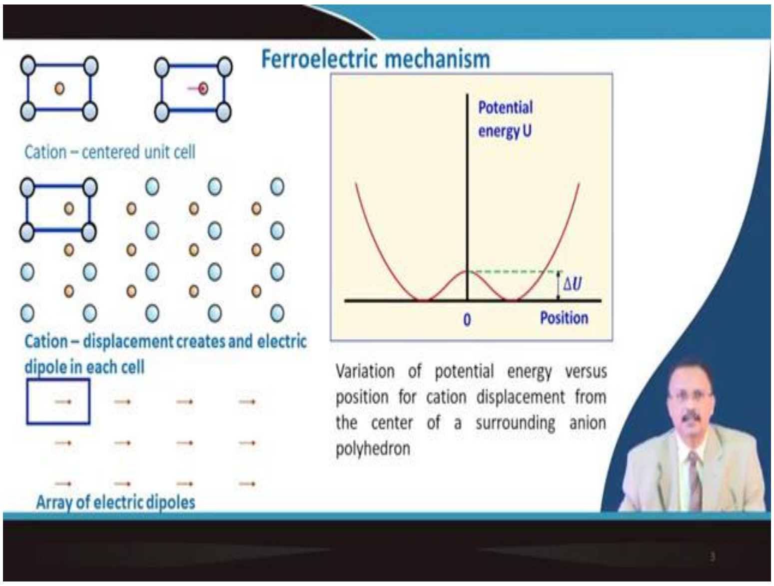

Ferroelectric mechanism

Cation – centered unit cell

Cation – displacement creates and electric dipole in each cell

Array of electric dipoles

Variation of potential energy versus position for cation displacement from the center of a surrounding anion polyhedron

Now, if you see this schematic, if you have this four ions which could be anion and this small ion, which is the cation. If this is exactly at the center, then the electric lines of force of this anions and the cation, they are exactly match. So, the charge is not separated by any distance. So, distance is 0.

So, the dipole moment is 0 in this material. But under certain situation, you will find that this cation is shifted from the central position. And usually their shifts shifted because of displacive phase transition. You will see the interrelation between the phase transformation and the electronic property of these non-metallic materials, and you can correlate it now.

So, once a structural phase transition takes place that forces this cation to go somewhere else, and there the charge is not balanced. So, there is charge separated by a distance. So, intrinsic dipole moment is there in this particular unit cell. So, we will call this is a spontaneously polarized material, because dipole moment per unit volume is nothing but polarization.

Now, once it happens that this particular cation is shifted to its right side, it has a cooperative phenomena. You see that it will actually influence all the unit cell to push this cation all in the right hand side. So, a region inside the crystal that will form where all these cations are shifted to the right hand side because of this mutual cooperative phenomena.

It is form a region here where the polarization direction are all identical. So, this kind of region we will term is as domain structure. So, in the domain structure, you have a array of electric dipoles which are all identically aligned. It is aligned in a particular direction. And remember there is no external electric field has been applied to this material.

So, once the polarization they are all aligned in a particular direction, so that means, there will be a creation of surface charge density. So, the electrical neutrality needs to be maintained. So, in order to maintain the electrical neutrality, there will be certain region in the same material where the polarization direction is reversed.

So, if tentatively if I assume that in a material you have only two types of this domain direction, which are basically separated by a very small distance I mean small energy barrier, so it can switch from here to here with the application of electric field right. So, this kind of material is termed as ferroelectric material.

They are spontaneously polarized, and they are having a domain structure. And this direction of the polarization is switchable from one to another by the application of a reverse electric field.

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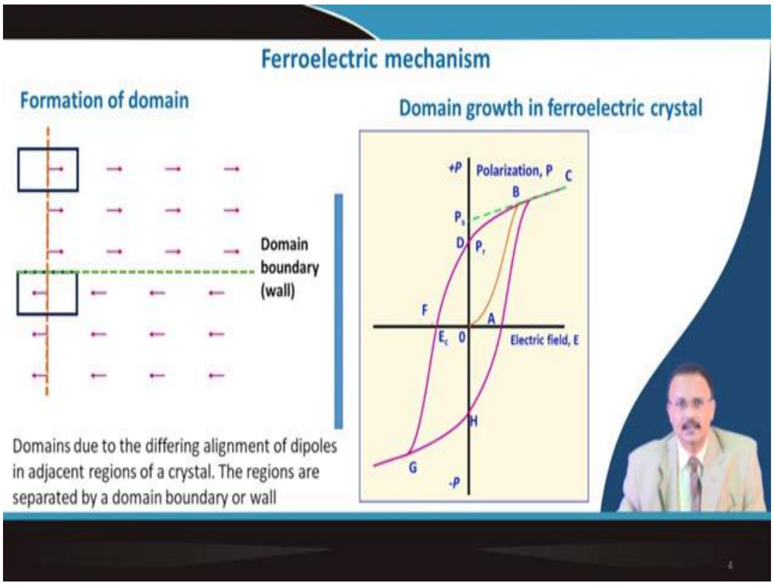

Ferroelectric mechanism

Formation of domain

Domain growth in ferroelectric crystal

Domain boundary (wall)

Domains due to the differing alignment of dipoles in adjacent regions of a crystal. The regions are separated by a domain boundary or wall

So, the formation of domain already I have explained that this region all are in one particular direction. So, in order to maintain the charge neutrality, you have this direction where the electric dipoles are in the reverse direction. It is separated by a small boundary. We call this is a domain boundary.

So, initially, at the virgin state when no field is applied, the polarization is 0 because certain things are this direction, certain things are in this direction, so as a whole, then it is electrically neutral. But whenever you are applying a field then according to the field direction this domain try to orient whichever is not favorably oriented.

So, at one stage at a particular field, all the domains are oriented along with the direction of the electric field. Now, once you reduce the field down to 0, then the polarization is not 0 like your linear dielectric material, but it has a remnant polarization which is denoted by the P r. And similarly at negative field direction also you have minus P r.

So, this ferroelectric material, once you apply an electric field, it is possible for you to switch the polarization direction in one direction to the other. So, the polarization is switchable, this spontaneously polarized material having switchable polarization. So, these are ferroelectric material.

There are other terms like saturation polarization, is it is the saturated value; although in this case it is not saturated as you can see. So, if it is not saturated, then you can draw a tangent here. And wherever it cuts the y-axis that is your saturation polarization value. And this is the maximum polarization value and the field that is required to switch one polarization state to another is known as coercive field. It is denoted by E_c.

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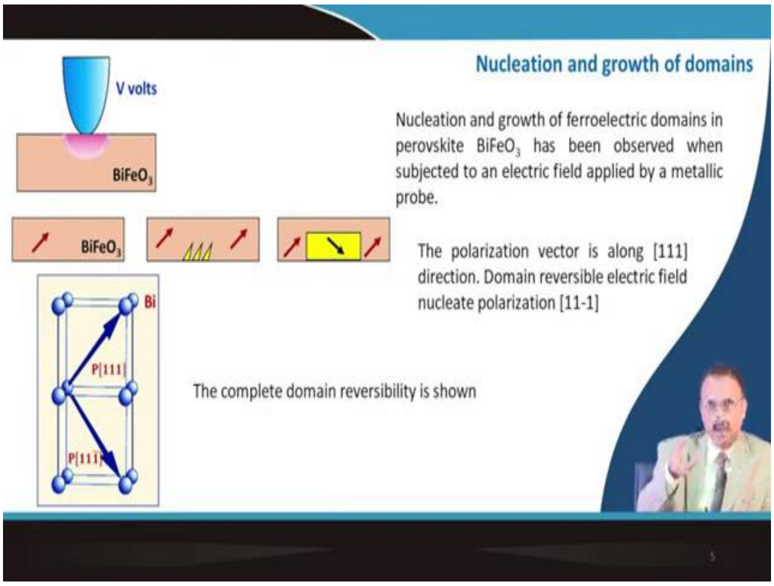

Nucleation and growth of domains

Nucleation and growth of ferroelectric domains in perovskite $BiFeO_3$ has been observed when subjected to an electric field applied by a metallic probe.

The polarization vector is along [111] direction. Domain reversible electric field nucleate polarization [11-1]

The complete domain reversibility is shown

So, this domain polarization, this can now be seen by a microscope, a piezo force microscope is used to actually see the domain and the orientation of the domain. I am not going into the details. But here is a typical example of a material which is otherwise ferroelectric and through the probe you are applying a electric field here. So, the polarization direction eventually they will all be in one particular orientation depending on the field that is being applied.

Now, once you try to reverse the polarization direction, then there will be a nucleation of the reverse domain at the bottom side of the sample. And after nucleation, it is just like nucleation and grain growth. This domain boundary will be mobile. And the polarization direction it is just opposite to this red arrow. So, it will grow, and eventually your polarization will be in the other side once you are applying a reverse electric field.

So, initially for this material, the polarization was along the body centered, body diagonal 111, and it is just reverse to 11 minus 1 direction with the application of a reverse electric field. This is for the nucleation and growth of this domain wall in this material.

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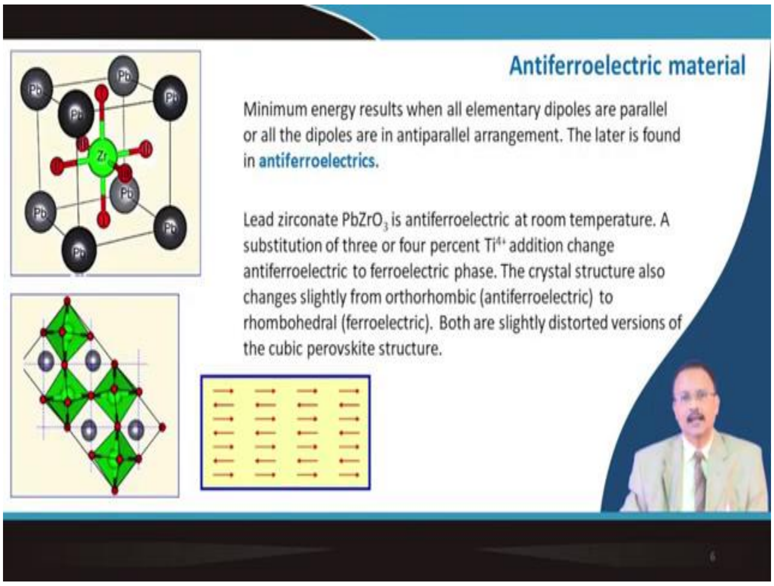

Antiferroelectric material

Minimum energy results when all elementary dipoles are parallel or all the dipoles are in antiparallel arrangement. The later is found in **antiferroelectrics.**

Lead zirconate $PbZrO_3$ is antiferroelectric at room temperature. A substitution of three or four percent Ti^{4+} addition change antiferroelectric to ferroelectric phase. The crystal structure also changes slightly from orthorhombic (antiferroelectric) to rhombohedral (ferroelectric). Both are slightly distorted versions of the cubic perovskite structure.

Certain material, they create a domain structure and this domain structure is actually you know that this is cancelled to each other. So, in a region all the polarization is oriented in one particular direction. But if you cross this domain boundary, then the polarization direction is such that they cancel to each other. So, the net polarization is 0. But in certain material within the unit self itself the polarization that is created, they are anti-parallel in nature.

And this type of material we call it is a anti-ferroelectric material – very limited materials exist which are antiferroelectric in nature, and lead zirconate titanate is one of them. So, it is also having a perovskite structure where Zr is within this octahedral cage, I have shown the octahedral cage here. Now, the shift of this jet cation in this octahedral cage is exactly reversed than that of the other octahedral case.

So, it is not the concept of the domain within the unit cell itself, they are anti parallelly arranged. And therefore, lead zirconate titanate they exhibits this antiferroelectric nature where the polarization in one unit cell is exactly cancelled by the polarization of the other unit cell.

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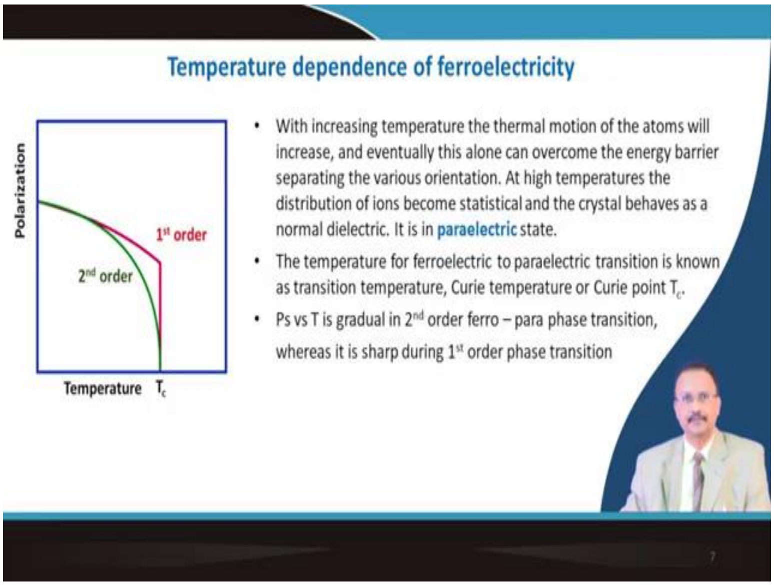

Temperature dependence of ferroelectricity

- With increasing temperature the thermal motion of the atoms will increase, and eventually this alone can overcome the energy barrier separating the various orientation. At high temperatures the distribution of ions become statistical and the crystal behaves as a normal dielectric. It is in **paraelectric** state.
- The temperature for ferroelectric to paraelectric transition is known as transition temperature, Curie temperature or Curie point T_c.
- Ps vs T is gradual in 2nd order ferro – para phase transition, whereas it is sharp during 1st order phase transition

So, the materials which are ferroelectric in nature I have explained that this two different state of polarization, they are separated by a very small barrier.

Now, if you increase the temperature along with increasing the tilt, for example, so what will happen? The temperature itself will help this cation to cross this barrier and go to the other minimum energy position. So, certainly this orderedness again here also order disorder kind of transformation is coming into picture.

So, this orderedness will be becoming in a disorder state. So, the polarization will reduce as a function of temperature. So, at a particular temperature, you will see it is all random. So, it does not matter the polarization is in this direction or this direction.

So, it is all random. So, the material will behave like a paraelectric material. They are non-linear dielectric. Their polarization will change in a non-linear fashion with the application of electric field, but there is no spontaneous polarization left.

So, it could be a first order type, where this kind of change of polarization as a function temperature is very dramatic. It is sharp or it could be a second order type where it is gradual in nature right. So, this is a second order phase transition. And where this sharp kind of transition takes place which is first order kind of phase transition, and the temperature where it takes place it is known as Curie temperature.

So, above the Curie temperature the material behaves usually isotropically it is cubic in nature. Once you cross this temperature it there is a displacive kind of polymorphic phase transformation takes place which is displacive in nature. And then the material transform into a ferroelectric state. And it remains ferroelectric once you cool it down. There could be another phase transition involved, but that depends on a typical material.

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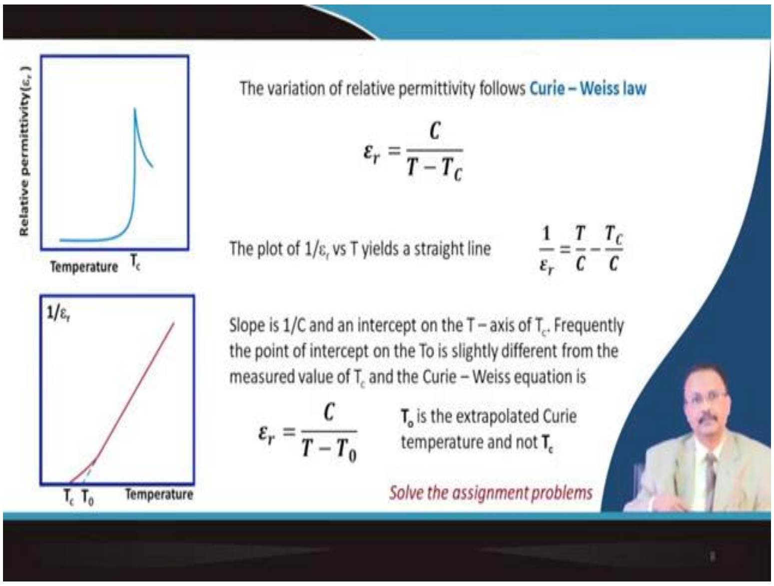

The variation of relative permittivity follows **Curie – Weiss law**

$$\varepsilon_r = \frac{C}{T - T_C}$$

The plot of $1/\varepsilon_r$ vs T yields a straight line $\frac{1}{\varepsilon_r} = \frac{T}{C} - \frac{T_C}{C}$

Slope is 1/C and an intercept on the T – axis of T_c. Frequently the point of intercept on the To is slightly different from the measured value of T_c and the Curie – Weiss equation is

$$\varepsilon_r = \frac{C}{T - T_0}$$

T_o is the extrapolated Curie temperature and not **T_c**

Solve the assignment problems

So, if you plot the dielectric constant as a function of temperature, then near the Curie temperature there is a very sharp transition as you can see here. So, this can be given by this relation that relative dielectric permittivity is dependent on Curie constant divided by T minus T C.

Here T C is the transition temperature. So, if you put T equal to T C, then your epsilon r will be undefined. So, very large dielectric constant you will get at this temperature. Below and above this temperature the dielectric constant is dramatically reduced. So, you can always reverse of the electric dielectric permittivity you can plot as a function of temperature.

So, it will be a linear plot as you can see. From the slope, you can get the curie constant and from the intercept, you can get the transition temperature. Usually the transition temperature is slightly different it is not this is a real linearity is maintained. So, the transition temperature is a bit lowered experimentally found. So, the exact temperature here is T 0.

So, you can extrapolate this linear part. So, T 0 is the extrapolated Curie temperature. And this is not really the T C which is experimentally verified where the maximum the dielectric constant takes place. So, we have certain assignment problem set to clarify these issues.

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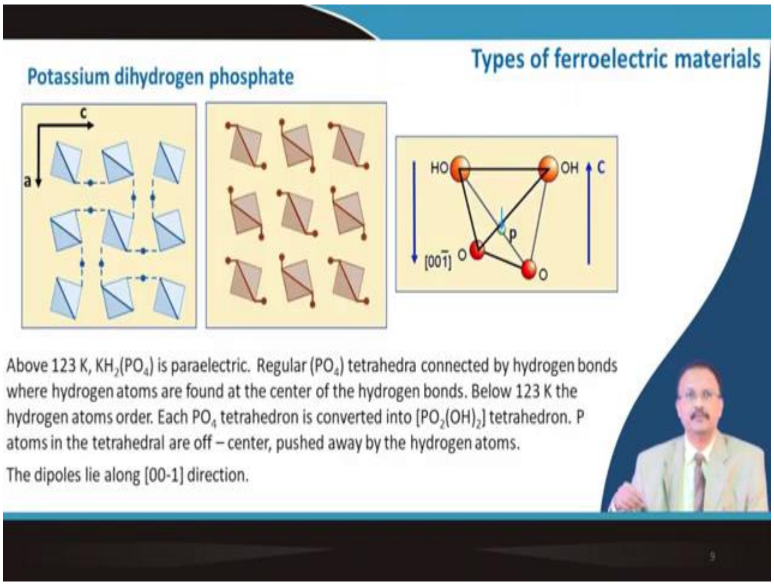

Types of ferroelectric materials

Potassium dihydrogen phosphate

Above 123 K, $KH_2(PO_4)$ is paraelectric. Regular (PO_4) tetrahedra connected by hydrogen bonds where hydrogen atoms are found at the center of the hydrogen bonds. Below 123 K the hydrogen atoms order. Each PO_4 tetrahedron is converted into $[PO_2(OH)_2]$ tetrahedron. P atoms in the tetrahedral are off – center, pushed away by the hydrogen atoms.

The dipoles lie along [00-1] direction.

So, there are various types of ferroelectric material. The first one is related with hydrogen bonding. So, the material is potassium dihydrogen phosphate. So, the hydrogen bonds you can see this, these are the bonds of hydrogen. And the regular PO 4 kind of tetrahedra they are linked with hydrogen bond. And as such above the T C, T C is quite low here around 123 degree Kelvin. Above the T C, there is no permanent dipole, it is in the paraelectric state.

But once you cool it down below this temperature, then the hydrogen position is shifted as you can see the hydrogen is shifted towards this. So, a individual tetrahedra now here it is hydrogen is coming and sitting very close to this oxygen and very close to this oxygen for this two apex oxygen. So, due to this the P cation this phosphate P cation is shifted from its symmetric position.

So, it induced a dipole. So, dipole moment per unit volume is polarization. So, below that transition temperature, the material is spontaneously polarized, and it exhibits the ferroelectric nature. It is of limited use because as you can see it is a very low temperature where the ferroelectricity you can see.

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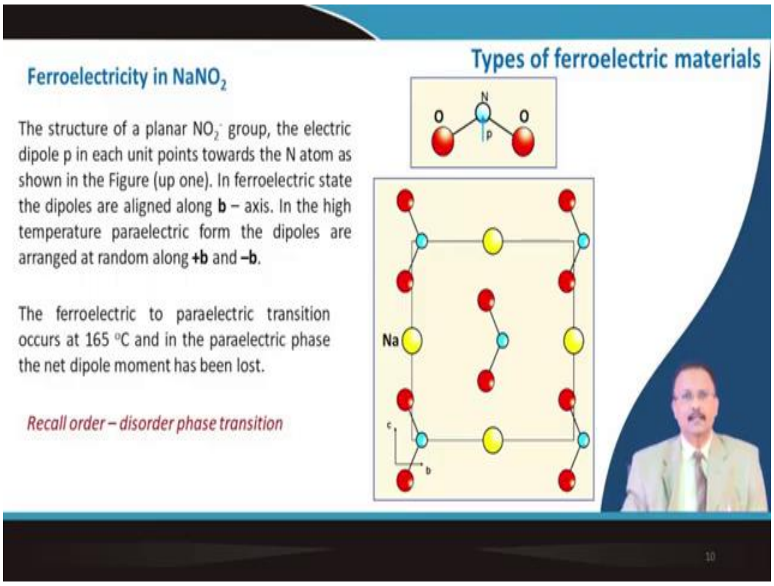

Types of ferroelectric materials

Ferroelectricity in $NaNO_2$

The structure of a planar NO_2^- group, the electric dipole p in each unit points towards the N atom as shown in the Figure (up one). In ferroelectric state the dipoles are aligned along **b** – axis. In the high temperature paraelectric form the dipoles are arranged at random along **+b** and **–b**.

The ferroelectric to paraelectric transition occurs at 165 °C and in the paraelectric phase the net dipole moment has been lost.

Recall order – disorder phase transition

Something similar this also I explained while I was talking about this order disorder phase transition. Sodium nitrite, here it is an arrow shaped material. And this dipole is very close to this nitrogen, nitrogen and oxygen, this bond is this dipoles are shown. So, when it is a disorder structure, then the material does not have any spontaneous polarization.

But, once it is below a certain temperature and here the Curie temperature is about 165 degree Celsius, then this is oriented in a arrowhead kind of direction is basically sodium chloride like structure where this octahedral positions are occupied by sodium and this is the nitrate ion. So, these are oriented and you get the ferroelectricity in it.

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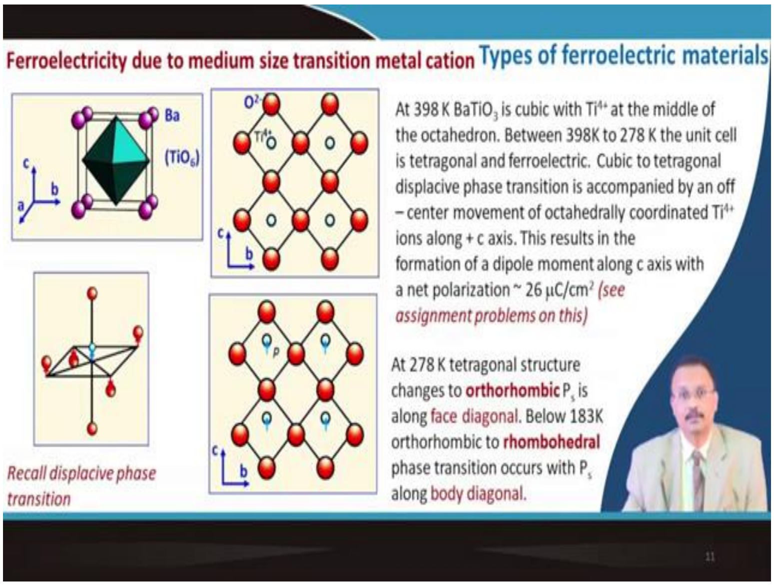

Ferroelectricity due to medium size transition metal cation Types of ferroelectric materials

At 398 K BaTiO$_3$ is cubic with Ti^{4+} at the middle of the octahedron. Between 398K to 278 K the unit cell is tetragonal and ferroelectric. Cubic to tetragonal displacive phase transition is accompanied by an off – center movement of octahedrally coordinated Ti^{4+} ions along + c axis. This results in the formation of a dipole moment along c axis with a net polarization ~ 26 μC/cm^2 *(see assignment problems on this)*

At 278 K tetragonal structure changes to **orthorhombic** P$_s$ is along face diagonal. Below 183K orthorhombic to **rhombohedral** phase transition occurs with P$_s$ along body diagonal.

Recall displacive phase transition

The prominent ferroelectric material is barium titanate. In cubic state, the titanium occupies this octahedral position. And once there is a phase transformation takes place at lower temperature, then the titanium position is either centrally up or it is down. So, once it is centrally up, then you do not have the matching of this two charge center. So, intrinsically the dipoles are created.

So, the creation of the dipole, that means, the polarization spontaneous polarization in this material is strongly related with this polymorphic phase transition from cubic to tetragonal state. In case of barium titanate, there are other two phase transition involved at relatively lower temperature from tetragonal, it converts to orthorhombic and from orthorhombic to rhombohedral.

So, this phase transition temperatures are not called Curie temperature. Curie temperature is only the temperature where it transform from a ferroelectric state to a paraelectric state. So, the polarization direction when cubic to tetragonal takes place that is the actual position is along z-axis.

When the other two phase transition takes place, then either it is along the phase diagonal of this FCC lattice or along the body diagonal only the polarization direction is changed.

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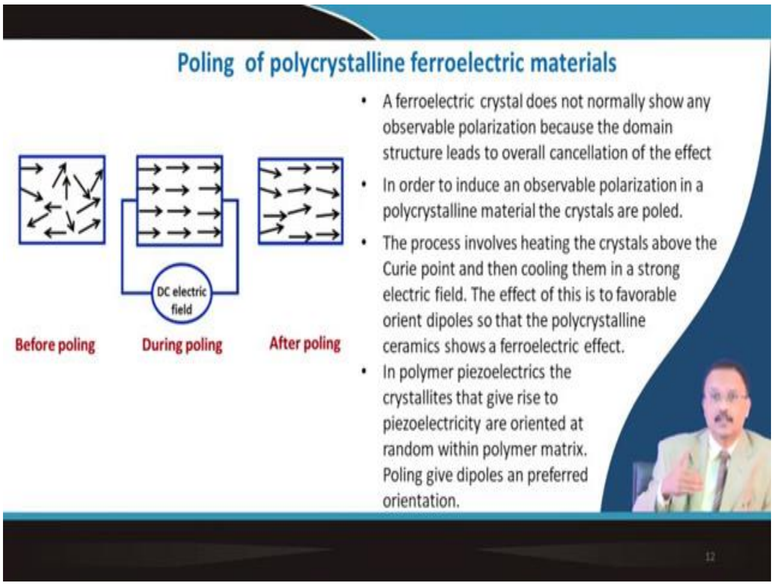

Poling of polycrystalline ferroelectric materials

- A ferroelectric crystal does not normally show any observable polarization because the domain structure leads to overall cancellation of the effect
- In order to induce an observable polarization in a polycrystalline material the crystals are poled.
- The process involves heating the crystals above the Curie point and then cooling them in a strong electric field. The effect of this is to favorable orient dipoles so that the polycrystalline ceramics shows a ferroelectric effect.
- In polymer piezoelectrics the crystallites that give rise to piezoelectricity are oriented at random within polymer matrix. Poling give dipoles an preferred orientation.

So, you can pull this material because as I said that the material is all random. So, you can increase the temperature to its respective Curie point. So, the material is so called soft. And then apply a strong electric field to orient this dipole direction to a particular direction along with the DC field direction.

And then with this field on you cool it down, so that it follows the hysteresis loop initially from the virgin state where all the dipoles are oriented in different direction. It is oriented in a particular direction, direction to the field. And then you turn on the field, and slowly cool the temperature, then it follows the reduction of the filled line and remnant polarization is there.

So, the material is polarized. And this operation is known as DC poling of the ferroelectric material.

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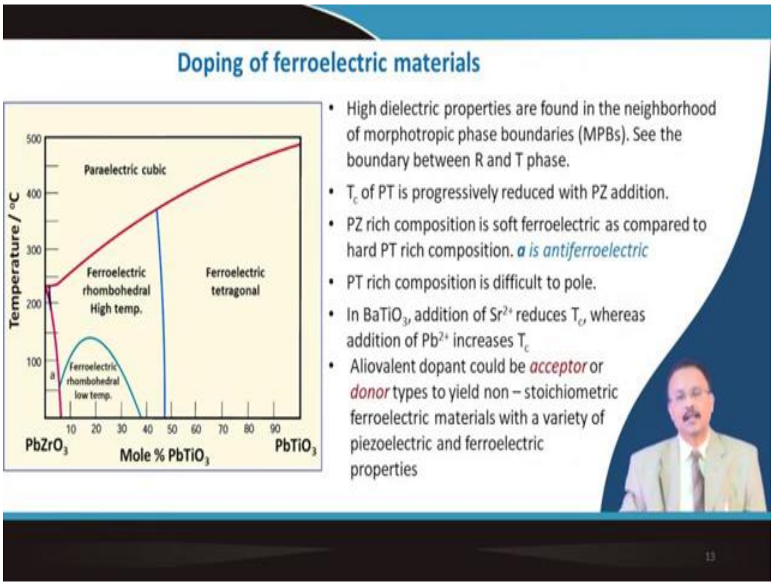

Doping of ferroelectric materials

- High dielectric properties are found in the neighborhood of morphotropic phase boundaries (MPBs). See the boundary between R and T phase.
- T_c of PT is progressively reduced with PZ addition.
- PZ rich composition is soft ferroelectric as compared to hard PT rich composition. ***a** is antiferroelectric*
- PT rich composition is difficult to pole.
- In $BaTiO_3$, addition of Sr^{2+} reduces T_c, whereas addition of Pb^{2+} increases T_c
- Aliovalent dopant could be *acceptor* or *donor* types to yield non – stoichiometric ferroelectric materials with a variety of piezoelectric and ferroelectric properties

So, the property of the ferroelectric material you can increase by the cation doping and or anion doping. And you know that it creates defects inside the lattice. And how exactly it can modify the property that is beyond the scope of this lecture, but I will cite one example lead titanate is tetragonal material, and it is perfect ferroelectric. Lead zirconate is anti ferroelectric in nature.

So, you can have a solid solution of lead zirconium titanate at a particular composition about fifty-fifty. You see that both the tetragonal and the rhombohedral phase coexist. So, there are different polarization direction, 6 for tetragonal, and 8 for rhombohedral. So, there are many polarization directions available. So, material can be easily pulled.

So, along with this phase and along with this composition, which we called morphotropic phase boundary there you will find that all the property piezoelectric coefficient, ferroelectric coefficient, pyroelectric coefficient. They are all increased tremendously along with this particular composition. So, this is a MPB composition for lead zirconate titanate.

Similarly, you can play with the composition at either b site or a site of this cation introduce defect in the lattice, either it will create cation vacancy, or it will create oxygen vacancies, and that can actually influence the domain dynamics and the ferroelectric property can be grossly modified or tuned by this dopant.

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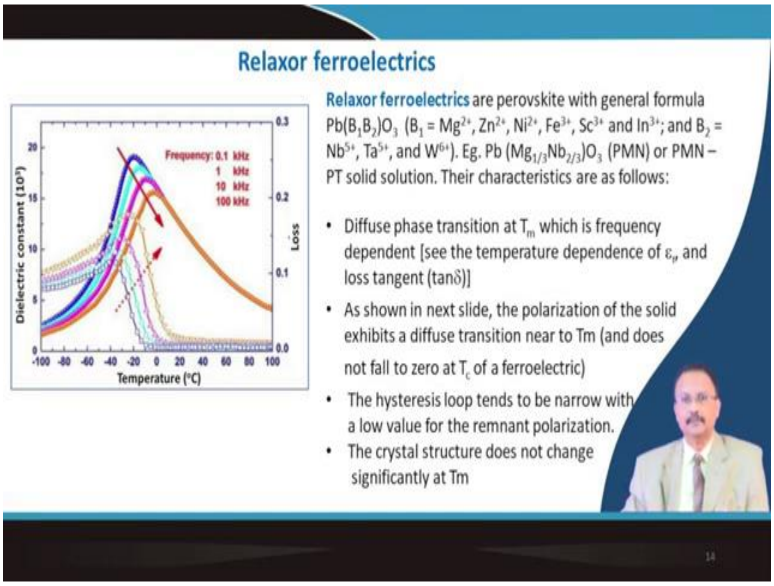

Relaxor ferroelectrics

Relaxor ferroelectrics are perovskite with general formula $Pb(B_1B_2)O_3$ ($B_1 = Mg^{2+}, Zn^{2+}, Ni^{2+}, Fe^{3+}, Sc^{3+}$ and In^{3+}; and $B_2 = Nb^{5+}, Ta^{5+}$, and W^{6+}). Eg. $Pb(Mg_{1/3}Nb_{2/3})O_3$ (PMN) or PMN – PT solid solution. Their characteristics are as follows:

- Diffuse phase transition at T_m which is frequency dependent [see the temperature dependence of ε_r and loss tangent ($\tan\delta$)]
- As shown in next slide, the polarization of the solid exhibits a diffuse transition near to Tm (and does not fall to zero at T_c of a ferroelectric)
- The hysteresis loop tends to be narrow with a low value for the remnant polarization.
- The crystal structure does not change significantly at Tm

Certain ferroelectric material type material they are quite interesting and they are called relaxor material. If you see the characteristics of this material instead in the B site you have two different types of cation, in lead zirconate titanate you had zirconia and titania both are plus 4 valence.

Here intentionally we are taking two different valance state materials. For example, the two valence state material magnesium plus 2, zinc plus 2, nickel plus 2 one can take, and you can take seemingly higher valence state material like niobium which is plus 5 state, tantalum you can use, tungsten you can use. So, there is a difference in the balance state within the unit cell which are randomly oriented.

In some unit cell, you have magnesium solid cell you have niobium, so that gives a property where the dielectric constant is not a very sharp function of temperature. So, you see that there is a broad dielectric maxima that is you are getting not a sharp dielectric versus temperature curve that you are getting. Now, with the increase of the frequency, this dielectric maxima goes towards higher frequency. And with increase of the frequency, the tan delta also moves to the higher frequency range.

So, these are the characteristics of the so called relaxer material. And you can see that the dielectric constant of this material at this dielectric maxima is very high it is about 20,000 dielectric constant you are getting out of this material. So, they are special type of material, and they are not really ferroelectric in nature.

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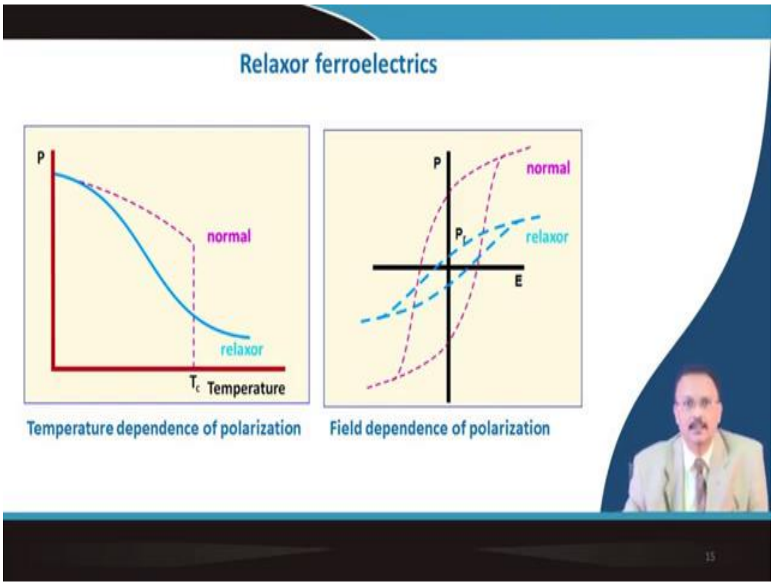

Relaxor ferroelectrics

Temperature dependence of polarization

Field dependence of polarization

If you see the difference here normal ferroelectric at the transition temperature, you see that there is a sharp drop of the polarization. But here you see the polarization there is no concept of this transition temperature because the phase transition does not occur. It remains in the same pseudo cubic phase.

So, you have the polarization which is continuing beyond the so called transition temperature or the maximum temperature corresponding to the dielectric maxima. And also if you cross the dielectric maxima, then the hysteresis loop is not really 0. Because what do you expect that a normal ferroelectric at T C. Beyond T C would not have any hysteresis loop, but here a slim kind of hysteresis loop in case of relaxer material also you are having.

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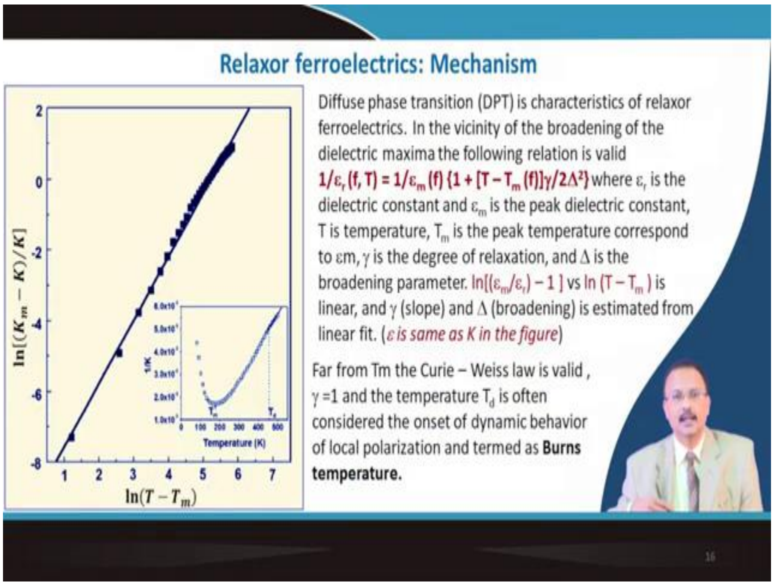

Relaxor ferroelectrics: Mechanism

Diffuse phase transition (DPT) is characteristics of relaxor ferroelectrics. In the vicinity of the broadening of the dielectric maxima the following relation is valid $1/\varepsilon_r(f, T) = 1/\varepsilon_m(f)\{1 + [T - T_m(f)]\gamma/2\Delta^2\}$ where ε_r is the dielectric constant and ε_m is the peak dielectric constant, T is temperature, T_m is the peak temperature correspond to εm, γ is the degree of relaxation, and Δ is the broadening parameter. $\ln[(\varepsilon_m/\varepsilon_r) - 1]$ vs $\ln(T - T_m)$ is linear, and γ (slope) and Δ (broadening) is estimated from linear fit. (*ε is same as K in the figure*)

Far from Tm the Curie – Weiss law is valid , γ =1 and the temperature T_d is often considered the onset of dynamic behavior of local polarization and termed as **Burns temperature.**

So, the mechanism is a bit complicated. And this mechanism is related to the polar nano region because of the two different charged species inside this material. So, this diffusion and this dielectric permittivity this relation is a bit complicated in this material. And I have written this relation of 1 by epsilon r.

You remember in case of the normal T C based ferroelectric material, it is epsilon r equal to C divided by T minus T C. But here if you write this inverse 1 by epsilon r, this follows this particular relation where you can see a gamma coefficient is there. And if you put gamma equal to 2, this is perfect relaxer. If this comma is equal to 1 that it translates into the normal this Curie temperature based ferroelectric material.

So, you can easily estimate the value of gamma and the broadness of this dielectric permittivity by plotting log of epsilon at maximum m divided by epsilon r minus 1 versus from this relation itself. You take log and then you plot a linear plot. And you can estimate the value of gamma, and it will take whether it is a perfect relaxer or it is in between a relaxer and ferroelectric material.

So, far from your maximum temperature may be the Curie law is valid. So, if you plot the relation for a relaxer material at very high temperature around this region which is far away from your maxima this temperature, it is valid here. And this from here you can have a specific temperature which we called the Burns temperature we can define it. So, this Burns temperature is far away from this maximum temperature where the Curie wise law is valid.

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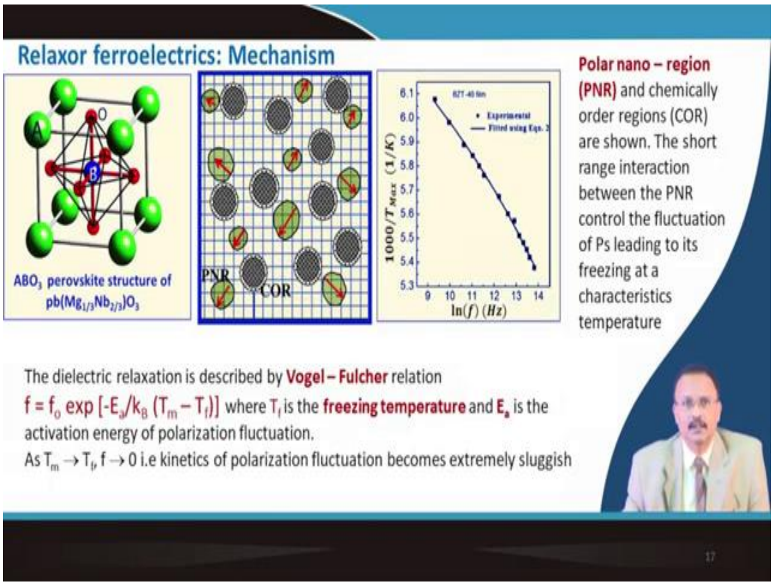

Relaxor ferroelectrics: Mechanism

ABO$_3$ perovskite structure of pb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$

Polar nano – region (PNR) and chemically order regions (COR) are shown. The short range interaction between the PNR control the fluctuation of Ps leading to its freezing at a characteristics temperature

The dielectric relaxation is described by **Vogel – Fulcher** relation

$f = f_0 \exp[-E_a/k_B(T_m - T_f)]$ where T_f is the **freezing temperature** and E_a is the activation energy of polarization fluctuation.

As $T_m \rightarrow T_f$, $f \rightarrow 0$ i.e kinetics of polarization fluctuation becomes extremely sluggish

So, it is due to a polar nano region something like this inside the otherwise matrix which is non polarizable. And this nano polar dimension, it shrinks basically when you go towards the maximum temperature region. But if you cool down the material temperature at lower temperature, they actually grows. And this frequency dependence it follows a Vogel-Fulcher kind of relationship. And I just explained it a little bit this while I was talking about the glass.

And this material shows a Vogel-Fulcher relationship, and you can actually get the freezing temperature where this kind of fluctuation of the polarization is grossly minimized and material behaves like a normal ferroelectric material. But if you increase the temperature very close to the maximum T m value, then it switches so fast that it really is in between a direct polarizable I mean spontaneous polarized material, and a paraelectric material. It is in between that stage.

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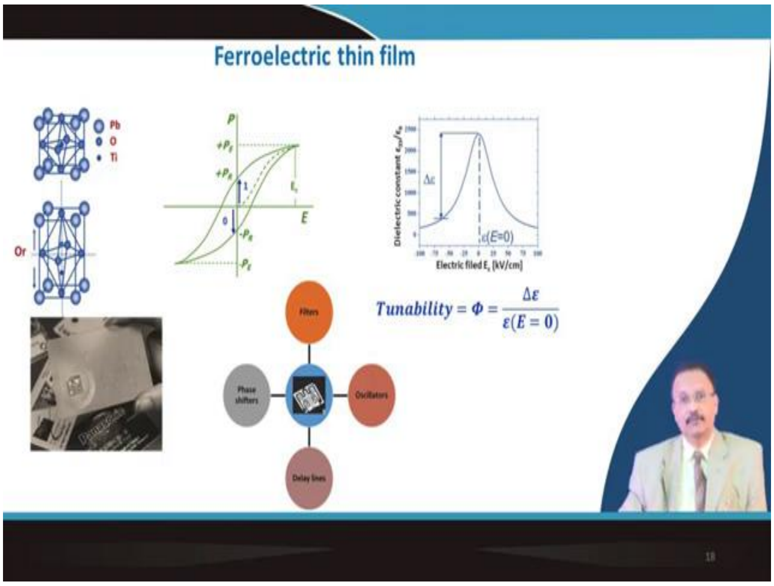

Ferroelectric thin film

$$Tunability = \Phi = \frac{\Delta\varepsilon}{\varepsilon(E=0)}$$

So, the ferroelectric thin film relaxer and ferroelectric in its paraelectric region they are a industrially very lucrative material. And relaxer ferroelectrics is mainly used for those places where high energy density is required because it has a very large star storage capacity. Normal ferroelectric material if you thin down the thickness, then it can be switched within 5 volt.

So, that therefore, in thin film state you can make lot of device. One such interesting device is a non-volatile memory where unlike the dynamic random access memory, you can store digital 1 and digital 0 in a matrix of the ferroelectric thin film memory. And digital 1 and 0 can be stored it can be switched very fast. So, very fast non-volatile memory device can be made.

But unfortunately the problem of fatigue because the polarization changes with number of read and write cycle that has not yet been overcome. So, it has not come into the market in a very big way. But in paraelectric state the tunability that is the change in the dielectric constant with the electric field that is an important parameter which can define various types of device like filter, oscillators, phase shifters, or delay lines, they are very very much lucrative for microwave communication.

So, this material or microwave dielectric material, which is having a transition temperature near room temperature. So, slightly above room temperature, they behave like a paraelectric material there is no hysteresis, but the dielectric is tunable, and this materials are very lucrative for communication kind of devices.

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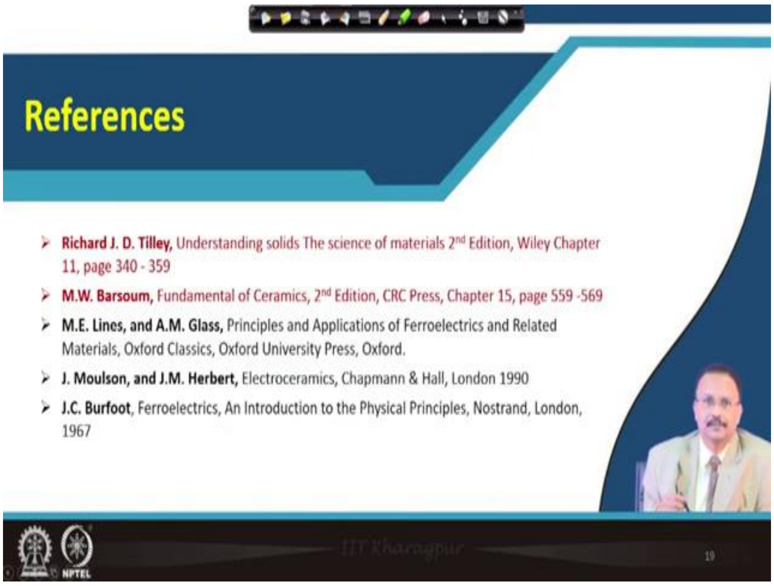

References

- **Richard J. D. Tilley,** Understanding solids The science of materials 2nd Edition, Wiley Chapter 11, page 340 - 359
- **M.W. Barsoum,** Fundamental of Ceramics, 2nd Edition, CRC Press, Chapter 15, page 559 -569
- **M.E. Lines, and A.M. Glass,** Principles and Applications of Ferroelectrics and Related Materials, Oxford Classics, Oxford University Press, Oxford.
- **J. Moulson, and J.M. Herbert,** Electroceramics, Chapmann & Hall, London 1990
- **J.C. Burfoot**, Ferroelectrics, An Introduction to the Physical Principles, Nostrand, London, 1967

So, this study material is the book by Tilley and also Barsoum the relevant chapters. And for a in depth study, you can consider the books by Lines and Glass and Moulson, or a very original book by J.C Burfoot.

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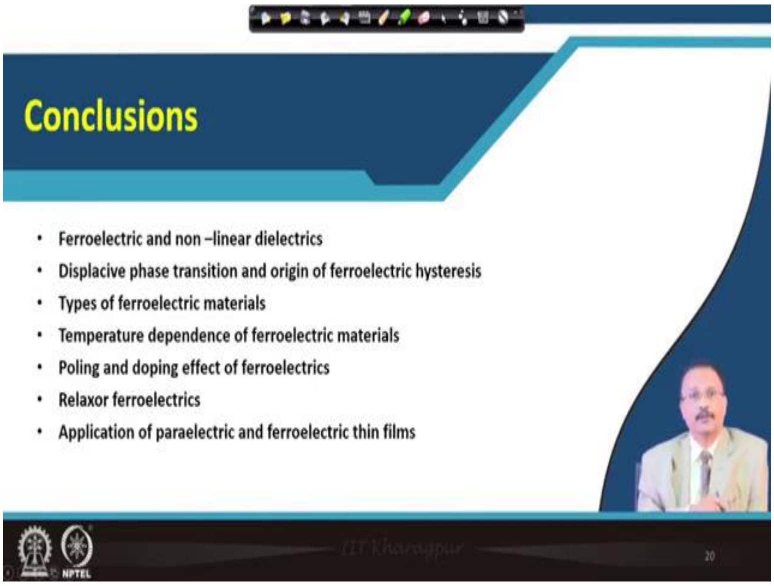

Conclusions

- Ferroelectric and non –linear dielectrics
- Displacive phase transition and origin of ferroelectric hysteresis
- Types of ferroelectric materials
- Temperature dependence of ferroelectric materials
- Poling and doping effect of ferroelectrics
- Relaxor ferroelectrics
- Application of paraelectric and ferroelectric thin films

So, we have talked about ferroelectric and non-linear dielectric material, displacive phase transition is the origin of the ferroelectric hysteresis, type of the ferroelectric material we have defined, then temperature dependence of the ferroelectric material pulling concept and use of the aliovalent dopants in controlling the ferroelectric properties. Then we have introduced the relaxer materials having very high dielectric permittivity.

And very brief overview of ferroelectric material in its ferroelectric state and in its paraelectric state in thin film form has been explained.

Thank you so much for your attention.